HOLLOW CORE PHOTONIC BANDGAP OPTICAL FIBER

Related Application

This application is a continuation of U.S. Application No. 10/099,044 filed on

5   March 13, 2002, and incorporated herein by reference.

Field Of The Invention

The present invention relates to optical fibers, and in particular to a hollow core photonic bandgap optical fiber.

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Background Of The Invention

Optical fibers are long, thin waveguide strands. They are used in a variety of applications involving the reception, transmission and detection of radiation, ranging from optical telecommunications to scientific instrumentation to ornamental displays.

15   Conventional optical fibers have a high-index core surrounded by a low-index cladding, a geometry that results in the total internal reflection of radiation entering the fiber over a select range of angles. Other forms of conventional optical fibers are referred to as "light tunnels" and use reflection from reflective walls rather than total internal reflection. Conventional optical fibers can have a variety of core geometries, including

20   elliptical cores, double cores, polarization-maintaining cores, and hollow cores.

Hollow core optical fibers are desirable where transmission losses need to be minimized, since in conventional optical fibers most of the radiation loss in an optical fiber occurs from absorption in the solid core. However, conventional optical fibers that depend on total internal reflection for waveguiding and confinement need to have a

25   core with a higher dielectric constant than that of the cladding. Such a structure is at odds with an optical fiber having a hollow central core, since air has a dielectric constant lower than all known practical cladding materials. Thus, hollow core optical fibers generally require specialized design considerations.

There are a number of different types of hollow core optical waveguides that operate on the either principle of total internal reflection or the principles of conventional reflection. For example, hollow optical waveguides through silicon wafers with highly reflective coatings on the side of the hollow core are disclosed in U.S. Patent No. 6,090,636 to Geusic et al. An optical fiber interconnect through a silicon wafer with a hole filled with two different dielectric materials is disclosed in U.S. Patent No. 6,150,188 to Geusic et al. A hollow optical fiber or hollow core waveguide consisting of a dielectric material coated with a highly reflective exterior coating is disclosed in U.S. Patent No. 5,815,627 to Harrington, wherein the hollow core can contain one guided wave and the annular ring another guided wave. A hollow core optical waveguide having a highly reflective coating on the inside of a glass tube is disclosed in U.S. Patent No. 6,141,476 to Matsuura.

As mentioned above, a desirable property for an optical fiber is minimal transmission loss. Accordingly, there has been significant effort to form optical fibers from materials that have high transmission and high reflection. Some of this effort has been directed to forming optical fibers from quasi-two-dimensional photonic crystals. A photonic crystal is a substrate within which is formed an array of period structures through which radiation of a particular wavelength or energy is forbidden to propagate. The result is a material with a very high reflectivity. Two-dimensional photonic bandgap crystal structures have been reported not only at optical wavelengths but at acoustic wavelengths as well.

It is well known in the semiconductor industry that a series of cylindrical holes judiciously formed in a solid semiconductor material can be used to form a quasi-two-dimensional photonic bandgap crystal. Figure 1 is a plan view of a conventional two-dimensional photonic crystal formed from a substrate 110 patterned with an triangular array of cylindrical holes 120.

An example prior art quasi-two-dimensional photonic bandgap optical fiber 210 is illustrated in Figures 2A and 2B. The optical fiber 210 includes an array of holes 220

formed within a cylindrical substrate 226. The fiber includes an outer cladding 228. A solid core 232, referred to as a "core defect," is at the center of the substrate. Radiation 242 is reflected within the bandgap of the photonic crystal produced by the periodic array of holes surrounding the core and is confined to the core. The radiation travels

5   down the length of the solid core by total internal reflection made possible by the low average index of refraction of the cladding as compared to that of solid core 232. Though optical fiber 210 is photonic crystal based, it utilizes total internal reflection like a conventional optical fiber and is relatively lossy because the solid core absorbs radiation.

10   Accordingly, what is needed is a photonic crystal optical fiber with a hollow core that allows for low-loss radiation propagation down the fiber by virtue of highly reflectivity walls as a result of the photonic bandgap of the crystal.

Summary Of The Invention

15   A hollow core photonic crystal optical fiber formed from several smaller hollow core optical fibers layered around a hollow core is shown. The fiber works on the principle of quasi-two-dimensional photonic crystals to confine radiation in a guided wave. The fiber has a true photonic bandgap in which radiation of a particular frequency (or equivalently, energy or wavelength) is totally forbidden, thereby

20   providing a very high reflection coefficient to radiation incident the walls of the hollow core.

The present invention includes an array of hollow core optical fibers arranged longitudinally about an axis to define a central hollow core about the axis. The array is formed so as to act as a quasi-two-dimensional photonic crystal with a photonic

25   bandgap that allows radiation of a select frequency range to propagate down the central hollow core.

The present invention further includes a plurality of hollow core optical fibers arranged longitudinally in an array having a two-dimensional triangular lattice structure

so as to form a quasi-two-dimensional photonic crystal having a photonic bandgap, and a central hollow core sized to accept radiation corresponding to the photonic bandgap. The hollow core optical fibers are, for example, conventional silica fibers.

The present invention also includes a system that includes a hollow core photonic bandgap optical fiber having an input end and an output end. The photonic bandgap optical fiber is made up of an array of hollow core optical fibers arranged longitudinally to form a two-dimensional photonic crystal lattice having a photonic bandgap. The array of optical fibers has at least one omitted optical fiber so as to leave a longitudinal central aperture that forms the hollow core in the array. The hollow core in the array is capable of guiding light having a frequency within the photonic bandgap of the array. The system further includes a radiation source optically coupled to the input end, and a photodetector optically coupled to the output end.

The present invention also includes a method of guiding radiation. The method includes forming a two-dimensional array of hollow core optical fibers to form a quasi-two-dimensional photonic crystal. The crystal has a photonic bandgap. In forming the array of fibers, at least one hollow core optical fiber is omitted. This creates a central hollow core in the array through which light of a select frequency that falls within the photonic bandgap is guided. The method further includes introducing radiation into the central hollow core having a frequency within the photonic bandgap.

These and other embodiments, aspects, advantages and features of the present invention will be set forth in part in the description which follows, and in part will become apparent to those skilled in the art by reference to the following description of the invention and referenced drawings or by practice of the invention. The aspects, advantages, and features of the invention are realized and attained by means of the instrumentalities, procedures, and combinations particularly pointed out in the appended claims.

Brief Description Of The Drawings

Figure 1 is a plan view of a conventional two-dimensional photonic crystal formed from a substrate and having triangular an array of cylindrical holes formed therein;

5   Figure 2A is a front-end view of a prior art photonic-crystal-based optical fiber having a plurality of holes surrounding a solid core;

Figure 2B is a cross-sectional view of the prior art optical fiber of Figure 2A taken along the line 2B-2B;

Figure 3A is a front-end view of an embodiment of the hollow core photonic

10   bandgap optical fiber of the present invention;

Figure 3B is a close-up front end view of the optical fiber of Figure 3A showing the individual conventional hollow core optical fibers making up the hollow core photonic bandgap optical fiber;

Figure 3C is a partial cross-sectional view of the optical fiber of Figure 3A as

15   taken along the line 3C-3C;

Figure 4A is a plot of the optimal filling factor F_{OPT} versus the background dielectric constant ϵ_B for a triangular lattice structure;

Figure 4B is a plot of the width of the photonic bandgap as fraction of the center frequency of the bandgap versus the background dielectric constant ϵ_B for a triangular

20   lattice structure;

Figure 5 is a face-on view of an alternate embodiment of the hollow core photonic bandgap optical fiber of the present invention that includes a cladding with a polygonal outer surface;

Figure 6A is a face-on view of an apparatus for forming the hollow core

25   photonic bandgap optical fiber of the present invention, showing first spools of fiber used to form the first layer of fibers on a rod;

Figure 6B is a side view of the apparatus of Figure 6A, showing second spools of fiber used to form the second fiber layer along with two of the heating units used to melt the fiber when it is pulled longitudinally off of the rod; and

Figure 7 is a side view of a system employing the hollow core photonic bandgap

5   optical fiber of the present invention.

In the Figures, the first digit of the reference number corresponds to the Figure number. Accordingly, like elements in different Figures have reference numbers that differ only in the first digit that identifies the Figure number.

10   **Detailed Description Of The Invention**

In the following detailed description of the embodiments of the invention, reference is made to the accompanying drawings that form a part hereof, and in which is shown by way of illustration specific embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled

15   in the art to practice the invention, and it is to be understood that other embodiments may be utilized and that changes may be made without departing from the scope of the present invention. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is defined only by the appended claims.

20   FIG. 3A is a a full front-end view of an embodiment of a hollow core photonic bandgap optical fiber 310 of the present invention. Optical fiber 310 includes an array 314 of coventional hollow core optical fibers 320 each longitudinally arranged about a central axis A1. Optical fibers 320 each having an endface 322, a hollow core 326 with a dielectric constant $\epsilon_0 = 1$, and an annular cladding 330 surrounding the hollow core

25   and having a thickness T and a dielectric constant $\epsilon_B > 1$. Note that the dielectric constant of hollow core 326 is taken as the free-space dielectric constant ϵ_0, which differs from that of air by only about six parts in ten-thousand. In an example embodiment, hollow core 326 is circular in cross-section and has a radius R2. For the

sake of discussion, optical fibers 320 are presumed hereinafter to have a circular hollow core.

FIG. 3B is a close-up front end view of optical fiber 310 of FIG. 3A. The total radius R1 of each fiber 320 is given by R1 = R2 + T. The total diameter of each fiber

5   is thus D1 = 2R1. The triangularly layered arrangement of fibers 320 omits at least one fiber from central axis A1, thereby leaving a longitudinal aperture or hollow core 340 centered on the central axis. Hollow core 340 is not exactly circular in cross-section, but has an effective circular cross-section 342 (dashed line). Also, hollow core 340 is also referred to hereinafter as a "central" hollow core to distinguish it from hollow cores

10   326 of the conventional optical fibers 320. Here, the word "central" is not intended to limit the location of the hollow core to the exact center of array 314.

Where optical fibers 320 have a circular cross-section, their arrangement in in array 314 forms small gaps 350. For fibers arranged in a triangular arrangement (Figure 3B), the gaps occur by virtue of the cusps 354 formed by placing two fibers together,

15   and then adding a third fiber to the first two fibers at the cusps.

In an example embodiment, fiber array 314 constitutes a two-dimensional photonic crystal with a triangular lattice structure and a lattice constant a = 2R1. The center wavelength and size of the bandgap of the photonic crystal depends on a number of factors, including the lattice constant a, and the difference (contrast) between

20   dielectric constants ϵ_0 and ϵ_B. It is convenient to define single parameter called the "filling factor," which is the ratio of the volume of empty space in the crystal to the total volume of the crystal.

FIG. 3C is a partial cross-sectional view of optical fiber 310 of FIG. 3A taken along the line 3C-3C. FIG. 3C illustrates how radiation 367 is guided in central hollow

25   core 340. In example embodiments, central hollow core 340 has an effective diameter D ranging anywhere from 0.5 microns to 5 microns, depending on the wavelength of radiation 367 to be guided. As a general rule, the longest wavelength of radiation capable of being accepted by the central hollow core is about twice the central core

diameter D. Thus, to form a hollow core photonic bandgap optical fiber capable of guiding infrared radiation of 1.5 microns for example, the diameter D of central hollow core 340 should be approximately 0.75 microns.

Because the photonic crystal formed by fiber array 314 is two-dimensional, the associated bandgap is in the directions orthogonal to radiation propagation down hollow core 330. For large incident angles θ (e.g., near degrees) measured relative to the central axis, the bandgap remains complete. For smaller angles, the bandgap width is reduced, and for increasingly large angles, the bandgap width is reduced and becomes incomplete. Thus, optical fiber 310 has a limited range of acceptance angles.

Figures 4A and 4B are plots adapted from Figures 4 and 6 of the article by M. Plihal et al., entitled "Photonic band structure of two-dimensional systems: The triangular lattice," Phys. Rev. B, 44 (16), 8565-8571, October 15, 1991, which article is incorporated by reference herein. Figure 4A plots a curve 410 of the optimal filling factor F_{OPT} as a function of background dielectric constant ϵ_B (also called the Ccontrastc) for a two-dimensional triangular lattice structure of cylindrical holes, such as shown in Figure 1. The optimal filling factor F_{OPT} is that which yields the widest bandgap for the lowest frequency. The results are applicable to the triangular lattice structure of fiber array 314 (Figure 3B). In an example embodiment, optical fibers 320 (Figures 3A-3C) are made of silica, which has a dielectric constant $\epsilon_B \sim 4$. From curve 410, it is seen that the corresponding optimum filling factor F_{OPT} is about 0.55 or 55%.

In an example embodiment, optical fibers 320 are selected and assembled to provide the optimum filling factor for optical fiber array 314, as described below. Figure 4B plots a curve 420 of the normalized width $W = (\omega_G a)/(2\pi c)$ of the photonic bandgap (i.e., the width of the bandgap as a fraction of the center frequency ω_G) versus the background dielectric constant ϵ_B. Here, c is the speed of light. It can be seen from curve 420 that for a background dielectric constant $\epsilon_B = 4$, the normalized width W of the bandgap is 0.08, or 8% of the center frequency ω_G.

Note also that the normalized width W of the bandgap depends directly on the lattice constant a, which is given by a = 2R1. Thus, the bandgap is determined by the radius R1 of optical fibers 320 used to form the optical fiber array/photonic crystal 314. Further, the frequency of radiation capable of being guided in hollow core 340 of optical fiber 310 is determined by diameter D of the central hollow core. Thus, the lattice constant a of optical fiber array 314 and the diameter D of central hollow core 340 formed therein are selected so that the frequency of radiation accepted by central hollow core 340 overlaps the photonic bandgap associated with the fiber array 314.

Designing fiber for a select filling factor

The design of optical fiber array 314 as shown in Figures 3A-3C is now described. The design process includes selecting a desired filling factor F.

To this end, first an imaginary triangle 364 of area A_T with vertices at the centers of three adjacent optical fibers 320 is formed (Figure 3B).

The area A_T of the imaginary triangle is given by:

$$A_T = 1/2(2R1)(R1)(3)^{1/2} = 1.73(R1)^2 \qquad \text{Equation 1}$$

The area A_C occupied by optical fibers 320 in area A_T (i.e., the total area A_T minus the area of gaps 350) is given by:

$$A_C = 3(1/6)\,\pi\,(R1)^2 = 1.57(R1)^2 \qquad \text{Equation 2}$$

The area A_A of air due to hollow cores 326 of optical fibers 320 in area A_T is given by:

$$A_A = (\pi/2)(R2)^2 = 1.57(R2)^2 \qquad \text{Equation 3}$$

The filling factor F is then defined as:

$$F = A_A / A_T = [1.57(R2)^2] / [1.73(R1)^2] \sim 0.91[(R2)^2 /(R1)^2] \quad \text{Equation 4}$$

5 Equation 4 is used to choose the radii R1 and R2 to obtain a select filling factor F. For example, filling factor F may be selected to be the optimum filling factor F_{OPT}. Using the example embodiment discussed above, $F = F_{OPT} = 0.55$, so that R2 = 0.78(R1).

 It is worth noting that the area associated with gaps 350 is small (e.g., about 10 10%), whereas the filling factor F needed to create a significant bandgap is generally in excess of 50%. Accordingly, gaps 350 generally do not constitute a significant perturbation to the photonic crystal lattice.

 Other embodiments of hollow core photonic bandgap optical fiber similar to that of optical fiber 310 are possible with the present invention. For example, with 15 reference to Figure 5, there is shown a hollow core photonic bandgap optical fiber 510 made up of an array of optical fibers 520 each having an elliptical cross-section hollow core 526 surrounded by a cladding 528 having a outer surface 538 with a polygonal cross-section (e.g., hexagonal, as shown). A polygonal hollow core 540 is centered on central axis A1. In an alternative embodiment to optical fiber 510, hollow cores 526 20 each have a circular cross-section. This alternate embodiment can be considered a special case of the elliptical cross-section hollow core embodiment.

 The polygonal cross-sections can be selected so that the filling factor in cases where gaps 350 are determined to be undesirable. Also, polygonal cross-section fibers may in some instances prove easier to stack when forming the hollow core optical fiber 25 array.

Method of fabrication

A method of forming the hollow core photonic bandgap optical fiber of the present invention is now described. For the sake of illustration, the method is described in connection with forming optical fiber 310 as shown in Figures 3A-3C, though the

5   method applies equally to other example embodiments.

Figure 6A shows front-end view of a fiber-forming apparatus 601 having a number (e.g., nine) of first spools 603 of conventional hollow core optical fiber 620. Each optical fiber 620 has an endface 622. First spools 603 are arranged radially outward from a central axis A2 of a forming rod 615. The forming rod has an outer

10   surface 617, an end 619 and a radius R_R. In an example embodiment, radius $R_R = R1$, or alternatively, $R_R \sim R1$.

Figure 6B is a side view of apparatus 601 of Figure 6A, showing a number of second spools 627 of optical fiber 620. Second spools 627 are also arranged radially outward from rod central axis A2 but are located closer to rod end 619 so that optical

15   fiber can be arranged over the forming rod or over existing layers of optical fiber placed onto the forming rod. Apparatus 601 includes a number of heat sources 643 are provided adjacent axis A2 in a position to provide heat to the optical fibers surrounding the forming rod..

The technique of forming the hollow core photonic bandgap optical fiber of the

20   present invention is similar to the method of forming a wound electrical cable. Thus, optical fibers 620 from first spools 603 are arranged so that a portion of each optical fiber lies along rod outer surface 617. These fibers form a first optical fiber layer 653. Next, more optical fibers 620 from second spools 627 are arranged so that a portion each fiber lies over the fibers in the first layer in cusps 654 formed by adjoining fibers

25   (Figure 3B). This forms a second optical fiber layer 657.

The process of layering opticcal fibers 620 from additional spools (not shown) is repeated until a desired number of layers is formed. Heat is then applied to the layered optical fibers via heat sources 643. When heated to the point where the fibers

begin to melt, the layers of optical fibers are pulled off of the forming rod along the direction of the rod axis A2. Optical fibers 620 unwind from the spools during the pulling (arrows 662), thereby forming a continuous optical fiber with a hollow core 640 centered on axis A1 coaxial with forming rod axis A2.

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Optical system with hollow core photonic bandgap optical fiber

With reference to Figure 7, there is shown an optical system 705. The system includes, in order along an axis A3, a radiation source 707, a first optional optical coupler 709, and a hollow core photonic bandgap optical fiber 710 according to the present invention. Optical fiber includes an input end 711, an output end 713, and a

10 hollow core 760. System 705 also includes a second optional optical coupler 727 adjacent output end 713, and a photodetector 737.

Radiation source 707 is capable of outputting radiation 767 of a frequency within the photonic bandgap of optical fiber 710. In one example embodiment, radiation source 707 is a laser, such as a laser diode. In another example embodiment,

15 radiation source 707 is an incoherent radiation source, such as a light-emitting diode or a conventional lamp.

First optical coupler 709 is an optical system designed to facilitate the coupling of radiation from radiation source 707 to hollow core 760 at input end 711 of optical fiber 710. Likewise, second optical coupler 727 is an optical system designed to

20 facilitate the coupling of radiation from hollow core 760 at output end 713 of optical fiber 710 to photodetector 737. First and second optical couplers can include any number or type of optical components, such as lenses, prisms and gratings.

In operation, radiation source 707 outputs a radiation signal 767 having a

25 frequency or range of frequencies within the photonic bandgap of optical fiber 710. Radiation source 707 may also output radiation at frequencies different than the photonic bandgap, but such radiation will not be guided as effectively, if at all, by optical fiber 710. In this sense, optical fiber 710 acts as a radiation filter.

Radiation signal 767 is coupled into hollow core 760 of optical fiber 710 over within a range of input angles by optical coupler 709. The radiation signal is confined to the hollow core by virtue of the photonic bandgap of the surrounding hollow core fiber array and propagates down the optical fiber. At the output end, the radiation

5 signal exits the hollow core and is collected by optical coupler 727, which directs the radiation signal to photodetector 737. The latter receives and detects the radiation signal and outputs a corresponding electrical signal 771, such as a photocurrent, which is further processed by an electronic device 777 downstream of the photodetector. In an example embodiment, electronic device 777 is a transimpedance amplifier that converts

10 a photocurrent signal to a voltage signal.

Conclusion

The present invention is a hollow core photonic bandgap optical fiber and method of forming same. The hollow core photonic bandgap optical fiber of the

15 present invention utilizes the advantages of a quasi-two-dimensional bandgap structure to provide a high reflectivity over a select radiation frequency range, while also providing a hollow core that minimizes radiation loss due to absorption. The photonic bandgap is formed by combining conventional hollow core optical fibers in an array along an axis but not on the axis, leaving a hollow core centered on the axis. The

20 diameter of the hollow core is sized to allow for the propagation of select radiation frequencies corresponding to the frequencies of the bandgap associated with the fiber array making up the hollow core photonic bandgap optical fiber.

Although specific embodiments have been illustrated and described herein, it will be appreciated by those of ordinary skill in the art that any arrangement that is calculated

25 to achieve the same purpose may be substituted for the specific embodiments shown. This application is intended to cover any adaptations or variations of the present invention. It is to be understood that the above description is intended to be illustrative, and not restrictive. Combinations of the above embodiments, and other embodiments

will be apparent to those of skill in the art upon reviewing the above description. The scope of the invention includes any other applications in which the above structures and fabrication methods are used. The scope of the invention should be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.